

A Design of the Low-Pass Filter Using the Novel Microstrip Defected Ground Structure

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Abstract—A new defected ground structure (DGS) for the microstrip line is proposed in this paper. The proposed DGS unit structure can provide the bandgap characteristic in some frequency bands with only one or more unit lattices. The equivalent circuit for the proposed defected ground unit structure can be explained. By using the derived and extracted equivalent circuit and parameter, the low-pass filters are designed and implemented. The experimental results show excellent agreements with theoretical results and the validity of the modeling method for the proposed defected ground unit structure.

Index Terms—Bandgap, defected ground structure, equivalent circuit, low-pass filter.

I. INTRODUCTION

A DEFECTED ground structure (DGS) for the microstrip line, such as various microstrip photonic bandgap (PBG) structures, which have periodic etched defects in backside metallic ground plane, is one of the most interesting areas of research. The PBG research was done in the optical fields originally, but the PBG structures can be applied to wide frequency ranges, including the microwave frequency band by properly scaled dimension. Recently, there has been an increasing interest in microwave and millimeter-wave applications of PBG circuits. [1]–[3] The only PBG structures, which have a periodic structure, have been known as providing rejection of certain frequency bands, i.e., bandgap effect. [4]–[8] Many passive and active microwave and millimeter devices have been developed to suppress the harmonics and realize the compact physical dimensions of circuits. Several efforts have been made to realize such devices on a various PBG circuits—e.g., a power amplifier with PBG circuits [9], [10], the PBG structure for slow-wave circuits [11], and realization of a magnetic wall in waveguide [12], [13]; their experimental results are sufficient to show the validity of PBG circuit applications. However, it is difficult to use a PBG structure for the design of the microwave or millimeter-wave components due to the difficulties of the modeling. There are too many design parameters, which have

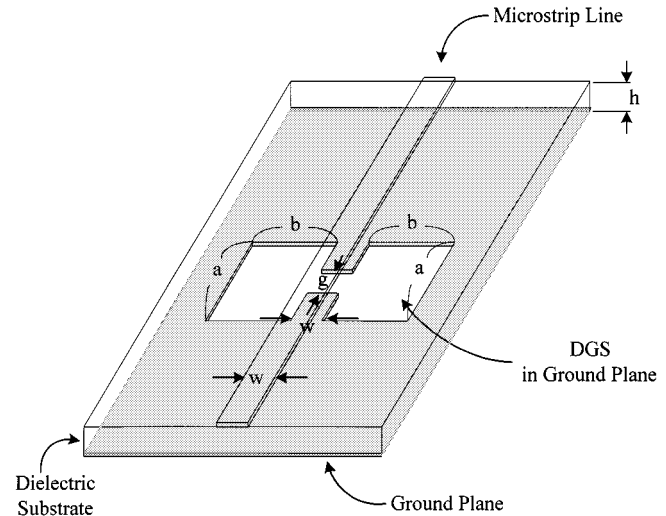


Fig. 1. Three-dimensional view of the proposed DGS unit section, which is etched in the ground plane of a microstrip line.

an affect on the bandgap property, such as the number of lattice, lattice shapes, lattice spacing, and relative volume fraction. Another difficulty in using this PBG circuit is caused by the radiation from the periodic etched defects.

In this paper, a new etched lattice shape for the microstrip is proposed as a unit DGS. An etched defect in ground plane disturbs the shield current distribution in the ground plane. This disturbance can change characteristics of a transmission line such as line capacitance and inductance. The proposed DGS consists of narrow and wide etched areas in backside metallic ground plane as shown in Fig. 1, which give rise to increasing the effective capacitance and inductance of a transmission line, respectively. Thus, an *LC* equivalent circuit can represent the proposed unit DGS circuit. The effects of physical dimensions of the proposed DGS on these equivalent-circuit parameters are described. It is the purpose of this paper to show a potential for applying the proposed DGS to practical circuits. To design a circuit with the proposed DGS section, the equivalent circuit and parameters for the DGS section should be extracted. In this paper, the equivalent circuit of the proposed DGS unit section is derived by using the field analysis method. The equivalent-circuit parameters are extracted based on the circuit analysis theory. By employing the extracted parameters and the circuit analysis theory, the bandgap effect for the provided DGS section can be explained. Three-pole low-pass filters are designed by using the proposed DGS sections and the equivalent circuit. A DGS section can be performed as a series element of

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a low-pass filter. The shunt capacitance for low-pass filters will be implemented by employing the open stub.

The low-pass filter using the DGS circuit has a number of attractive features, which include the following.

- 1) The structure is very simple
- 2) The stopband is very wide and more deeper than that of a conventional low-pass filter.
- 3) The insertion loss is very low.
- 4) Extremely small element values for implementation of low-pass filter can be realized.

The validity of the modeling method for the proposed DGS unit section and the design method for the low-pass filter is verified by experiments.

II. FREQUENCY CHARACTERISTICS OF DGS

Fig. 1 shows the etched lattice shape of the proposed DGS section, which is located on the backside metallic ground plane. The proposed DGS unit section can provide cutoff frequency and attenuation pole in some frequency without any periodic array of DGS. In order to investigate the frequency characteristics of the DGS section, we simulated the DGS unit section by Ansoft HFSS V.6.0. The simulation results show that one-pole low-pass filter characteristics, as expected. Existing of the cutoff frequency means that employing the DGS section increases the effective permittivity so that the effective inductance of a microstrip is also increased. The cutoff frequency is mainly dependent to the etched square area in ground plane. There is also attenuation pole location, which is due to the etched gap distance. Actually, it is well known that an attenuation pole can be generated by combination of the inductance and capacitance elements. Thus, to explain the frequency characteristic of the proposed DGS section, the presence of a capacitance factor should be needed. The etched gap area, which is placed under a conductor line, as shown in Fig. 1, provides the parallel capacitance with effective line inductance. Thus, the proposed DGS section is fully described by two parameters: the etched lattice dimension and gap distance. We showed the influences of these two parameters on frequency characteristics of a microstrip by simulations. All simulations were carried out by three-dimensional (3-D) HFSS.

A. Influence of the Square Lattice Dimension

The linewidth was chosen to be the characteristic impedance of 50- Ω microstrip line for simulations. Three DGS unit circuits without any period were simulated with the different dimension. In order to investigate the influence of the square lattice dimension, the etched gap, which is related with the gap capacitance, was kept constant to 0.2 mm for all three cases and the etched square area was varied. The substrate with 62-mil thick and a dielectric constant of ten was used for all simulations. The simulation results are illustrated in Fig. 2. From Fig. 2, one clearly observes that employing the proposed etched lattice increases the series inductance to the microstrip line. This effective series inductance introduces the cutoff characteristic at certain frequency. As the etched area of the unit lattice is increased, the effective series inductance increases, and increasing the series in-

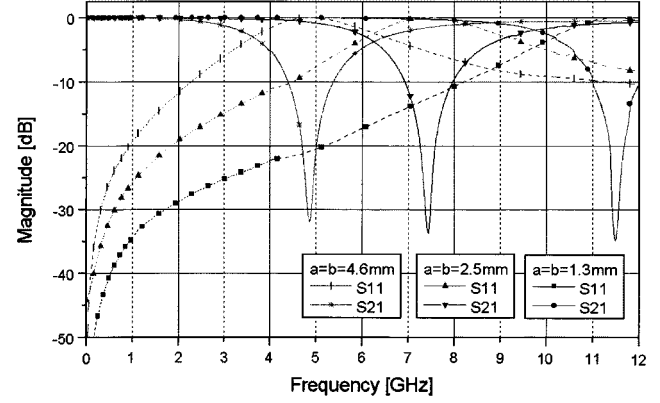


Fig. 2. Simulated S -parameters for the proposed DGS unit lattices. The gap distance g is 0.2 mm for all cases. The lattice dimension is $a = b = 1.3$ mm, $a = b = 2.5$ mm, and $a = b = 4.6$ mm, respectively. The substrate with 62-mil-thick and a dielectric constant of ten was used for all cases.

ductance gives rise to a lower cutoff frequency, as seen in Fig. 2. There are attenuation poles in simulation results on the etched unit lattices. These attenuation poles can be explained by parallel capacitance with the series inductance, as was explained previously. This capacitance depends on the etched gap below the conductor line, which is noted as g in Fig. 1. The capacitance values are identical for all cases due to the identical gap distance. However, the attenuation pole location, which corresponds to the resonance frequency of the parallel LC circuit, also becomes lower because as the series inductance increases, the resonance frequency of the equivalent parallel LC circuit decreases.

B. Influence of the Gap Distance

We now investigate the influence of the etched gap distance. The lattice dimension $a \times b$ was kept constant to 2.5 mm \times 2.5 mm for all three cases and the etched gap distance was varied. The simulation results are shown in Fig. 3. Due to the constant lattice dimensions, we can expect that the effective series inductances are also constant for all cases. Unlike the influence of lattice dimension, there is no change in cutoff frequency despite the variation of the gap distance. This means that the gap distance does not affect the effective series inductance of a microstrip. Variation of the effective capacitance only affects the attenuation pole location, as seen in Fig. 3. As the etched gap distance increases, the effective capacitance decreases so that the attenuation pole location moves up to higher frequency. Simulation results seen in Fig. 2 and Fig. 3 pertinently show the influences of the proposed DGS section on frequency characteristics.

This equivalent circuit of the proposed DGS unit can explain the bandgap effect. The series inductance due to the DGS section increases the reactance of a microstrip with the increasing of the frequency. Thus, the rejection of the certain frequency range can be started. The parallel capacitance with the series inductance provides the attenuation pole location, which is the resonance frequency of the parallel LC resonator. However, as the operating frequency increases, the reactance of the capacitance decreases. Thus, the bandgap between the propagating frequency bands can be occurred.

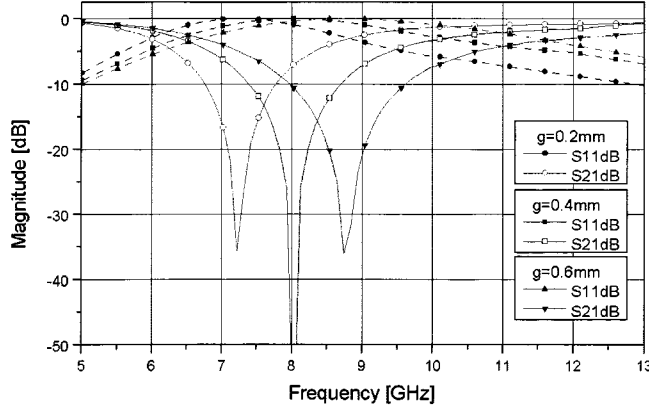


Fig. 3. Simulated S -parameters for the proposed DGS unit lattices. The lattice dimension is $a = b = 2.5$ mm for all cases. The gap distance is $g = 0.2$ mm, $g = 0.4$ mm, and $g = 0.6$ mm, respectively. The substrate with 62-mil-thick and a dielectric constant of ten was used for all cases.

III. MODELING AND PARAMETER EXTRACTION

In the previous section, we have shown that the parallel LC circuit can represent the equivalent circuit of the proposed DGS section. Furthermore, effects of the proposed DGS parameters on the frequency characteristics have been investigated. From a practical point-of-view, the DGS section can serve as replacements for a parallel LC resonator circuit in many applications. To apply the proposed DGS section to a practical circuit design example, it is necessary to extract the equivalent circuit parameters. As an example of the parameter-extraction procedure, a , b , w , and g , which are dimensions of the DGS section shown in Fig. 1, have been chosen to be 5, 5, 2.4, and 0.5 mm, respectively. The substrate for simulations was an RT/Duroid 5880 with 31-mil-thick and a dielectric constant ϵ_r of 2.2. The simulation result is shown in Fig. 4 where solid lines are simulations by using 3-D HFSS. There is an attenuation pole near 8 GHz in the field simulation result. Fig. 4 shows the one-pole low-pass filter with an attenuation pole. In order to explain the cutoff and attenuation pole characteristic of the proposed DGS section simultaneously, the equivalent circuit should exhibit performances of low-pass and bandstop filter at the same time. Thus, the simple circuit shown in Fig. 5 can explain the phenomenon for the proposed DGS section.

The circuit parameters for the derived equivalent circuit can be extracted from the simulation result. The simulation result of the proposed DGS unit section can be matched to the one-pole Butterworth-type low-pass response, which has 3-dB cutoff frequency at 3.5 GHz. The series reactance value shown in Fig. 5 can be easily calculated by using the prototype element value of the one-pole Butterworth response. The prototype element value is given by various references. [14], [15] The parallel capacitance value for the given DGS unit dimension can be extracted from the attenuation pole location, which is parallel LC resonance frequency, and prototype low-pass filter characteristics by using the following procedures. The reactance value of the proposed DGS unit can be expressed as follows:

$$X_{LC} = 1/\omega_o C \left(\frac{\omega_o}{\omega} - \frac{\omega}{\omega_o} \right) \quad (1)$$

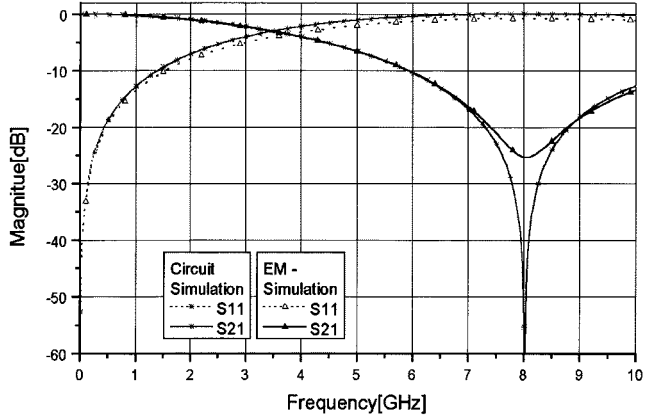


Fig. 4. Simulation results for proposed DGS unit section. The lattice dimension is $a = b = 5$ mm. The gap distance is $g = 0.5$ mm. The substrate with 31-mil-thick and a dielectric constant ϵ_r of 2.2 was used for simulation.

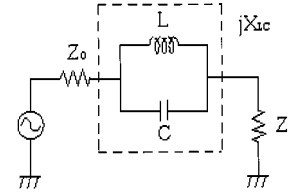


Fig. 5. Equivalent circuit of the proposed DGS circuit, where the dotted box shows the DGS section.

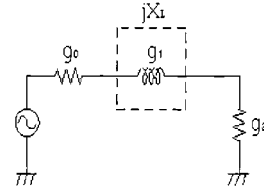


Fig. 6. Butterworth-type one-pole prototype low-pass filter circuit.

where ω_o is the resonance angular frequency of the parallel LC resonator, which is corresponding to attenuation pole location in Fig. 4. The series inductance of the Butterworth low-pass filter, shown in Fig. 6, can be derived as follows:

$$X_L = \omega' \cdot Z_o g_1 \quad (2)$$

where ω' denotes the normalized angular frequency, Z_o denotes the scaled impedance level of the in/out terminated ports, and g_1 is given by the prototype value of the Butterworth-type low-pass filter. In order to have the low-pass filter characteristics, the equivalent circuit of proposed DGS unit section, shown in Fig. 5, should be equal to the prototype low-pass filter, shown in Fig. 6, at a certain frequency. The equality at the cutoff frequency of the low-pass filter is given by the following:

$$X_{LC}|_{\omega=\omega_c} = X_L|_{\omega'=1} \quad (3)$$

From above equality, the series capacitance C of the equivalent circuit, shown in Fig. 5, can be obtained as follows:

$$C = \frac{\omega_c}{Z_o g_1} \cdot \frac{1}{\omega_o^2 - \omega_c^2} \quad (4)$$

TABLE I
EXTRACTED EQUIVALENT-CIRCUIT PARAMETERS FOR THE PROPOSED UNIT DGS SECTION. THE GAP DISTANCE g IS 0.2 mm FOR ALL CASES

	DGS dimensions		
	$a = b = 1.3\text{mm}$	$a = b = 2.5\text{mm}$	$a = b = 4.6\text{mm}$
Inductance (nH)	0.3675	0.865945	1.97725
Capacitance (pF)	0.51222	0.52845	0.537947
Cutoff Frequency (GHz)	10.15	6.085	3.62
Attenuation pole Location (GHz)	11.6	7.44	4.88

TABLE II
EXTRACTED EQUIVALENT-CIRCUIT PARAMETERS FOR THE PROPOSED UNIT DGS SECTION. THE LATTICE DIMENSION IS $a = b = 2.5$ mm FOR ALL CASES

	DGS dimension		
	$g = 0.2\text{mm}$	$g = 0.4\text{mm}$	$g = 0.6\text{mm}$
Inductance (nH)	0.81051	0.90712	0.96825
Capacitance (pF)	0.60286	0.43306	0.34247
Cutoff Frequency (GHz)	6	6.4	6.72
Attenuation pole Location (GHz)	7.2	8.03	8.74

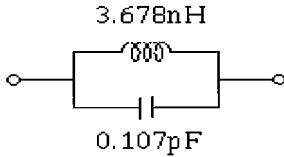


Fig. 7. Extracted equivalent-circuit parameters of the proposed DGS unit section, which has $a = b = 5$ mm, $w = 2.4$ mm, and $g = 0.5$ mm, respectively. The substrate with 31-mil-thick and a dielectric constant ϵ_r of 2.2 was used for simulation.

Once the capacitance value of the equivalent circuit is extracted, the series equivalent inductance for the given DGS unit section can be calculated by the following:

$$L = \frac{1}{4\pi^2 f_o^2 \cdot C} \quad (5)$$

where f_o is the frequency of the attenuation pole location and C is the extracted series capacitance value. Therefore, we can obtain each equivalent-circuit parameters by using (4) and (5), as shown in Fig. 7 [16]. Tables I and II show the extracted equivalent-circuit parameters for the proposed DGS unit sections, which are simulated in Figs. 2 and 3.

The equivalent-circuit simulation result using the obtained equivalent-circuit parameters is shown in Fig. 4 for comparison with the field calculated result. As show in Fig. 4, the equivalent-circuit simulation result shows excellent agreement with field calculations. Thus, the derived equivalent circuit and parameters for the proposed DGS section can be directly adapted

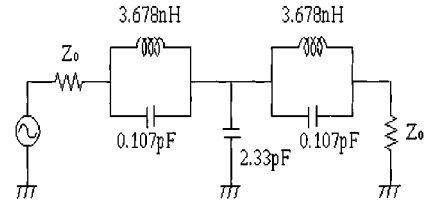


Fig. 8. Three-pole lumped low-pass filter with the equivalent circuits of a DGS unit section. The cutoff frequency is 1.3 GHz with 0.01-dB ripple level.

to design a practical circuit. In the following section, we will demonstrate an example for low-pass filter design with the derived equivalent circuit and parameters.

IV. LOW-PASS FILTER DESIGN AND MEASUREMENTS

In order to show the validity of the equivalent circuit and extracted parameters for the proposed DGS unit section, three-pole low-pass filters with attenuation pole were designed by employing the proposed DGS unit structure at the cutoff frequency of a 1.3-GHz with 0.01-dB ripple level. Fig. 8 shows the lumped low-pass filter circuit with the equivalent circuit for DGS unit structure. The lumped low-pass filter circuit can be easily obtained from the prototype low-pass element values by proper frequency and impedance scaling. The parallel capacitance in a lumped low-pass filter can be realized by using the parallel open stub. The open stubs are realized with a T-junction structure and cross-junction structure, respectively. Fig. 9 shows a schematic of the designed low-pass filters with the proposed

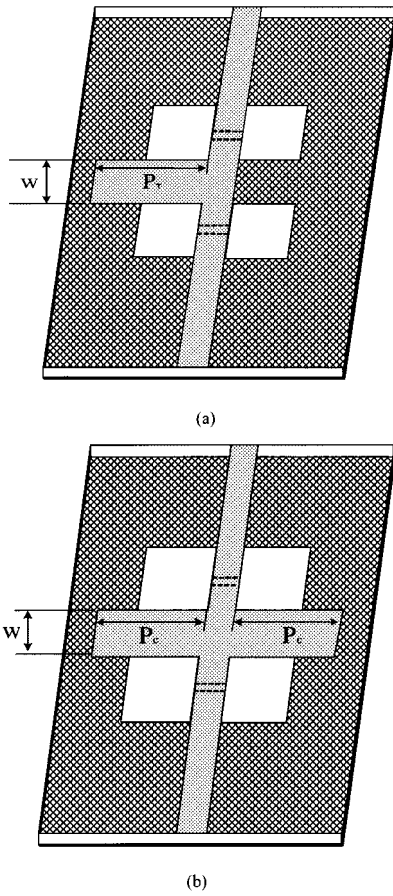


Fig. 9. Schematics of designed low-pass filters with the proposed DGS unit sections. (a) T-junction opened stub for parallel capacitance where the stub width w and length P_T are 5 and 10 mm, respectively. (b) Cross-junction opened stub for parallel capacitance where the stub width w and length P_C are 5 and 6 mm, respectively.

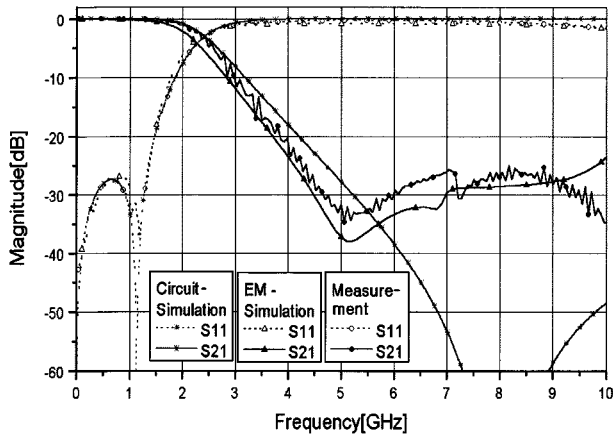


Fig. 10. Measured results for the fabricated DGS low-pass filter using the T-junction-type open stub with simulated data of a low-pass filter for comparison.

DGS sections. To implement the high-impedance inductance with a conventional microstrip, the conductor width becomes narrow. This is a limitation to use a microstrip low-pass filter configuration for high-power applications. By employing the proposed DGS sections, extremely small element values for implementation of a low-pass filter can be realized. Furthermore,

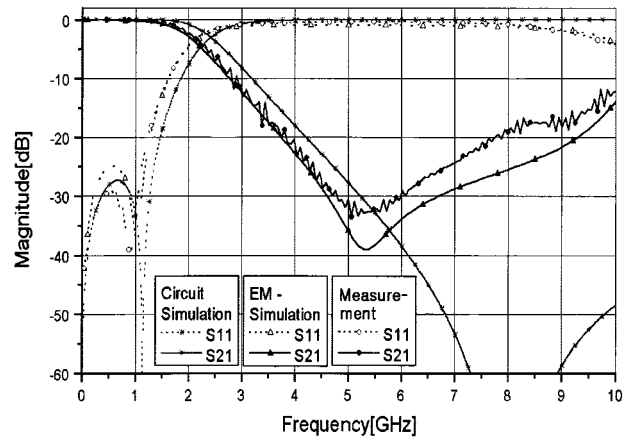


Fig. 11. Measured results for the fabricated DGS low-pass filter using the cross-junction-type open stub with the simulated data of a low-pass filter for comparison.

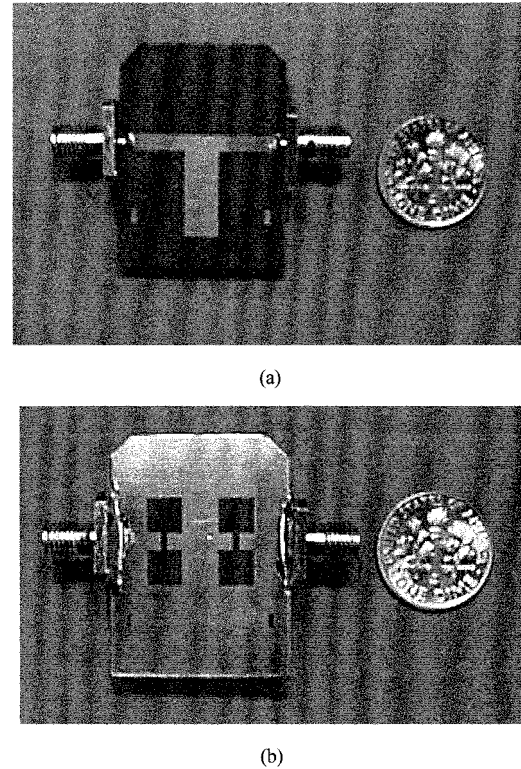


Fig. 12. Fabricated DGS low-pass filter with T-junction-type open stub. (a) Top view. (b) Bottom view.

the high-impedance inductance sections were realized by using DGS sections with a conductor width corresponding to a 50- Ω microstrip so that it can be expected that for DGS low-pass filters improve the power-handling capability.

Fig. 10 shows measured results for the fabricated DGS low-pass filter using the T-junction-type open stub with simulated data of a low-pass filter for comparison. Furthermore, Fig. 11 shows the comparison between measured results for the fabricated DGS low-pass filter with the cross-junction-type open stub and simulated data. Measurements and field calculations were carried out with absorbing boundary circumstance. Thus, these measurements and field calculations

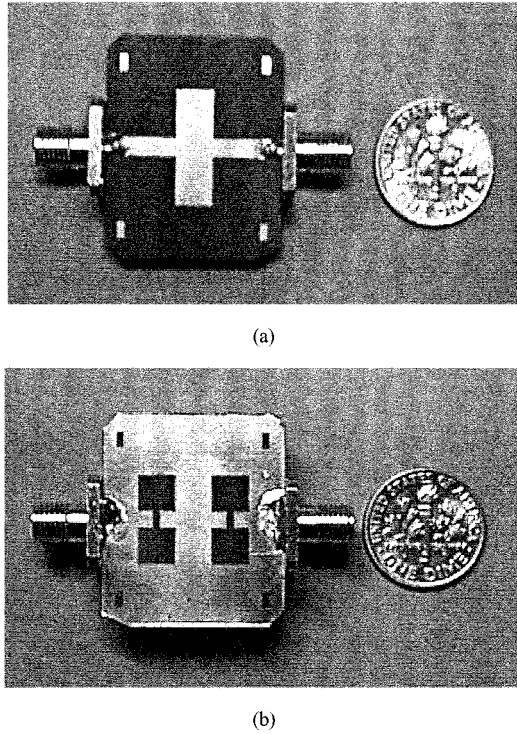


Fig. 13. Fabricated DGS low-pass filter with cross-junction-type open stub. (a) Top view. (b) Bottom view.

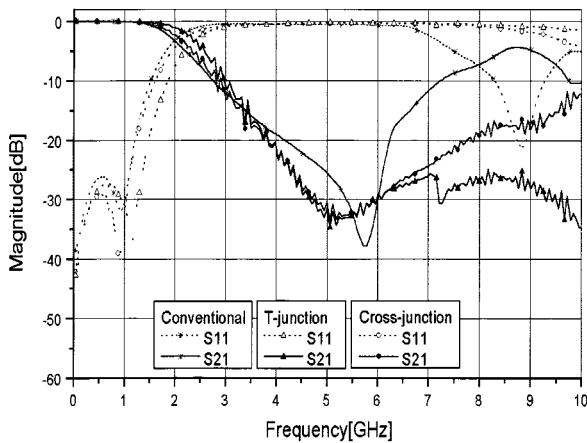


Fig. 14. Comparison of measured results for the fabricated DGS low-pass filters with the T-junction, cross-junction-type open stub, and conventional low-pass filter.

show differences with circuit simulated data in stopband due to radiation at DGS sections. Employing a metallic boundary for measurements and field calculations might show the improved stopband calculation. Figs. 12 and 13 show photographs of the fabricated low-pass filters with DGS section. The fabricated low-pass filters with the proposed DGS sections show relatively very simple configurations. To show the improved stopband characteristics of the DGS low-pass filters, we designed conventional low-pass filters with the same design specifications. Fig. 14 shows experimental results for the fabricated DGS low-pass filters using the T- and cross-junction-type open stub with the measured data of conventional low-pass filters as references. The attenuation characteristics for fabricated DGS

low-pass filters show more than 20-dB filters up to 8 GHz. As can be seen, harmonic responses of conventional microstrip low-pass filters were started near 6 GHz. On the other hand, the DGS low-pass filters have relatively wider and deeper stopband characteristics than those of conventional low-pass filters. The measured insertion and return losses are less than 0.15 and 20 dB for all DGS low-pass filters, respectively. The measured data for fabricated DGS low-pass filters shows very low-level insertion and radiation loss, which could be generated by DGS, at the passband frequency range. The validity of the modeling method for the proposed DGS unit section and the design method for the low-pass filter is verified by experiments.

V. CONCLUSIONS

In this paper, the new DGS unit section and its equivalent circuit have been proposed. By using a simple circuit analysis method, the equivalent-circuit parameter extraction method for the proposed DGS unit section has also been derived. Furthermore, by employing the extracted parameters, the bandgap effect for the provided DGS section was explained based on circuit analysis theory. In order to show the validity of the proposed DGS structure and the derived equivalent circuit, the three-pole low-pass filters have been designed, fabricated, and then measured. Numerical simulations using 3-D HFSS show good agreement with experiments. The proposed DGS sections can realize small element values for implementation of a low-pass filter. Furthermore, the fabricated low-pass filter with the proposed DGS sections is expected to provide the improved the power-handling capability because that DGS section can implement the high impedance inductance line with broader conductor width than that of a conventional microstrip. The proposed DGS low-pass filters also have wider and deeper stopband characteristics than those of conventional low-pass filters. The measured data for fabricated DGS low-pass filters shows fairly good insertion-loss characteristic. This newly proposed DGS section and its equivalent circuit could also find various applications such as a bandpass filter, phase shifter, and multipole switch.

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